

Dynamic Optical Interconnect

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Technical Field

The present invention relates, in general, to the field of optical telecommunications and compensated imaging. More particularly it relates to a system and method for creating an optical link between two stations, each station not necessarily being in the line of sight of the other.

Background

The prior art includes systems for relaying optical information between two beacons. This is conventionally accomplished by first detecting and demodulating the optical information received by the first beacon from an optical source, subsequently synthesizing a optical beam by modulating another optical source with this information, and, finally, directing the new optical beam to the second beacon. This multi-element repeater system has application to well-defined relay modules, along optical fiber links for example, or for $N \times M$ interconnects for photonic networks, among others. However, in the general case, where propagation errors may be dynamic, and where the incident beams can arrive over a large field-of-view, a more robust interconnection system is required. These problems and limitations are addressed by this invention.

The prior art also includes systems comprising a set of tilt-mirror compensators which are used for correcting certain errors. Such systems can only compensate for the lowest-order errors such as tilt and astigmatism errors. Other low-order errors, such as focus, can be corrected with a variable focus element. However, these systems are unable to compensate for higher order propagation errors such as general wavefront distortions due to propagation through turbulent atmospheres, multi-mode optical fibers, etc. Thus, a system and method are needed that provide ways of compensating for these errors.

The present invention addresses the general case of phase (wavefront) errors. In this connection, the prior art includes the Double-pumped Phase Conjugate Mirror (DPCM). The DPCM does not require any servo-loop devices, since it proceeds via an all-optical nonlinear interaction. However, the DPCM requires the power carried by the incident laser beam to be above a given threshold, in order to properly function. This threshold generally ranges between a few $\mu\text{W} / \text{cm}^2$ to a few mW / cm^2 , depending on the particular crystal used for the DPCM. Some examples of adequate crystals include BaTiO_3 and InP. Moreover, the response time of a DPCM depends on the intensity of the incident beams, and the intensities of the two incident beams need to have similar values for the device to function optimally (fast response time, stable operation, and suitable wavefront compensation). Finally, the DPCM is lossy and the insertion loss can be large, approaching 30% or more.

In contrast, the present device has a very low insertion loss (it only requires enough light to be sensed by the wavefront error sensor), and can function with input beams with intensities which need not to be equal (i.e., not necessarily balanced). Similar to conventional adaptive optical systems, the wavefront compensation capability will be a function of the number of equivalent pixels, or phase actuators, relative to the number of resolvable coherent phase patches which need to be phased up or corrected.

One object of the invention is to provide a system and method for relaying optical information from one transceiver to another. Specifically, this invention will direct a first optical beam emanating from a first transceiver and travelling to a second transceiver, into the reverse direction of a second optical beam emanating from the second transceiver and traveling to the first transceiver. The beams can be encoded, so that a communication link is realized with diffraction-limited capability. In its most basic form, a simple pair of tilt mirrors may be used to direct one beam into the reverse direction of the other. However, in general, the beams are not plane waves, and may have undergone time-varying (i.e., dynamically varying) propagation distortions, including atmospheric distortions, multi-mode fiber-induced distortion, etc. Therefore, an adaptive optical element is preferably used to compensate for, and to track out, these undesirable time-varying distortions, and, at the same time, provide a means for coupling the light from one direction into the other, and vice versa (without loss of the desired modulation). Since this system provides for coupling of the two optical beams, no local detector or source is required at the location of the interconnect module. Moreover, the optical beams that leave the interconnect

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module propagate in precisely the reverse direction of the incident beams (i.e., they are mutually phase-conjugate replicas of the incident beams). Thus, pointing and tracking is realized with this system, so that the system performance is not compromised (i.e., low insertion loss and high directivity). Finally, modulation is preserved on the various beams, so that information can be transferred from one station to another station, with diffraction-limited performance, and subject to typical adaptive optical design issues and constraints, such as diffraction, dispersion, depolarization, the compensation bandwidth, the spatial bandwidth of the system (e.g., the number of resolvable pixels for wavefront reconstruction), etc.

10 Applications of the present invention include optical "relay nodes" for free-space, space-based or terrestrial-based, as well as for guided-wave based (e.g., coupling of the output of a single or multi-mode fiber to another fiber or to a free-space path), optical communication and image relay links, or combinations thereof. Many applications do not afford the luxury of line-of-sight viewing between the stations at the end points of the communication link. For example, a 15 mountain may obstruct the end points for direct viewing, or two satellites may no longer "see" each other. To overcome this problem, an intermediate "relay node" or interconnection system is required, which may be placed on a hilltop or on an intermediate satellite, such that the interconnection system is in the line of sight of both stations. It may also be necessary to optically relay (one-way or two-way) information from one subsystem (e.g., a multimode fiber) 20 into another subsystem (e.g., an array of optical modulators, detectors, etc.).

As shown in Fig. 1, the prior art discloses a method to first detect and demodulate the beam (originating from a first station) at the mid-point (e.g., hill-top) of the link between two stations, then to encode this information onto another laser, and finally direct the encoded data to a second station to complete the link (on the other side of the hill-top). This approach, however, does not
5 compensate for propagation distortions.

The present invention provides for an automatic re-directing of the beam, as it arrives at the hill-top, to the second half of the link, as shown in Fig. 2. Moreover, the invention compensates for propagation distortions, so that the beam will arrive at the other end of the link without distortion. This invention enables such an intermediate node to be realized, without the usual photonic repeater requirements of high-bandwidth photo-detection, modulation and retransmission of the data. In this invention, the temporal modulation format imposed onto the beam from its initial point of origin is preserved. As it goes through the interconnection system only its wavefronts are modified, while its temporal encoding is maintained. Further, the system can function using mutually incoherent sources (e.g., free-running lasers at each end point of the link). When both of these lasers impinge onto the system, the beam from one of the end-points will be directed into the wavefront-reversed direction of the path that the second beam took, thereby "finding" and arriving to the other end of the link distortion-free (assuming usual time scale of beam formation by the system, range, atmosphere distortion time scale, and motion of
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20 the source locations during the optical transit time).

Additionally, the system of the present invention provides for "auto-tracking". Indeed, if the end-point stations are moving, the interconnect can track or follow the moving stations. This assumes that the stations move slowly with respect to the reconfiguration time of the interconnect and the time/spacial scale of the dynamic distortions. The system provides for
5 propagation-distortion compensation as well.

A related application is in the area of space-based low-cost relay mirrors. A pair of large-area telescopes are used to collect a weak signal, and then relay the beam to another location. These lightweight mirrors, which may be made of thin membranes (mylar, etc.), often possess optical distortions because the lightweight material they are made of can easily deform. The system performance is thereby degraded. By placing the proposed invention between the pair of large-area relay mirrors, the local mirror aberrations, as well as path distortions experienced by the two incident beams, can be corrected in real-time. Other potential areas of application include stratospheric relay platforms, such as LEO and MEO satellites and other airborne systems, with application to backbone feeder lines, as well as dynamic links for optical fibers, laser sources and beam combining systems. In the latter case, a given incident probe beam can be used as a local reference beam, which can, as a result of the interconnection system, phase up a collection of single-frequency, but randomly phased oscillators, including optical fiber amplifiers and oscillators.

Summary

This invention provides a novel system that can adaptively interconnect two incoherent optical beams thereby creating an optical link between two stations. This invention also provides a
5 method of optically interconnecting two stations from which two optical beams emanate, the two optical beams being directed from the two stations to a common location such as a hilltop.

The overall scope of this invention is to provide a dynamic interconnect capability to couple a pair of spectrally narrowband or broadband optical beams, which may carry modulation information. By way of an example, let us suppose that two optical beams emanate from transceivers at two different locations, and are both incident upon the optical interconnection system of the present invention. The system will direct each beam into the reverse (i.e., phase conjugate) direction of the other, so that each transceiver will detect the beam that emanated from the other station.

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In general, the incident beams propagate along different paths, and, thus, may experience different propagation distortions, beam wander, etc. This invention provides an interconnection system for optical beams which may have experienced different Doppler shifts, possess different wavefront distortions, speckle, as well as depolarization (the latter two cases would involve the
20 use of additional SLMs (Spatial Light Modulators).

The system architecture comprises a pair of closed-loop Adaptive Optical (AO) modules (or, two regions on a common-focus correction module, the latter for bore-sighting the two beams and adaptive optical element), in conjunction with an optional tilt-focus compensator for low-order aberration errors, if necessary. Also comprised in the system are a number of reflectors and beam
5 splitters. Each AO module is controlled by a given input beam.

The system of this invention is not a conventional repeater device. That is, it does not merely detect and demodulate the beam, and then encode the information onto another optical source (e.g., a relay station). Instead, it re-directs one optical beam into the reverse direction of another by modifying its wavefronts. In this manner, the system compensates for wavefront errors along the paths of the two incident beams, resulting in a well-defined output beam, with near-diffraction-limited performance. Moreover, any global modulation information is preserved on each incident beam, which is redirected into the reverse path of the other beam. Therefore, no demodulation and subsequent repeater-based modulator elements are required, thereby greatly simplifying the basic system architecture. If necessary, however, optical amplifiers can be placed at any point along the system (including at the interconnect module). The interconnect module will provide compensation for optical distortions in the amplifiers as well.

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Brief description of the drawings

Fig. 1 illustrates a prior art system for exchanging optical information between two stations, the line of sight between the two stations being obstructed by a hill.

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Fig. 2 shows that the interconnect of the present invention may be used for optical information exchange between two stations, even though the line of sight between the two stations is obstructed by a hill.

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Fig. 3A depicts an embodiment of this invention wherein the AO modules function in reflection mode, and wherein a pair of optical tilt-focus error compensators is used;

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Figs. 3B depicts an embodiment of this invention wherein the AO modules function in reflection mode, and wherein a single optical tilt-focus error compensator is used;

Fig. 4 depicts an embodiment of this invention wherein the AO modules function in transmission mode.

Fig. 5 depicts an embodiment of this invention wherein a single AO module is used, the AO module comprising a single AO wavefront corrector having two regions, and a pair of Wavefront error sensors.

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Detailed description

An embodiment of this invention is illustrated with reference to Fig. 3A, another embodiment is illustrated with reference to Fig. 3B, and yet another embodiment is shown with reference to Fig. 4. The systems of Figs. 3A and 3B relate to an optical interconnect functioning in reflection mode, whereas the system of Fig. 4 relates to an optical interconnect functioning in transmission mode. The following description applies equally to both the reflection-mode systems of Figs. 3A and 3B and the transmission-mode system of Fig. 4. When appropriate the distinctions between these two systems are made clear.

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For the purpose of illustration, beam 9 originating from station A, and beam 10 originating from station B, are shown displaced relative to one another. In actuality, the two beams travel on top of one another, in opposite directions.

20 The system allows two stations, A and B, to exchange information via an optical link created between them using an interconnect. The interconnect preferably comprises a pair of Adaptive

Optical (AO) modules 3 and 4, each of which comprising a pair of AO wavefront correctors 3a and 4a, and a pair of Wavefront Error Sensors 3b and 4b to drive AO wavefront correctors 3a and 4a respectively. The interconnect further comprises a pair of optical tilt-focus error compensators 7 and 8, placed upstream and downstream of the AO modules, respectively, and a

5 pair of beam splitters 17 and 18 placed between the AO modules. Tilt-focus error compensator 7 is positioned between station A and AO module 3 such that tilt-focus error compensator 7 is in the light path between station A and AO module 3. Similarly, tilt-focus error compensator 8 is positioned between station B and AO module 4 such that tilt-focus error compensator 8 is in the light path between station B and AO module 4. Alternatively, the configuration shown in Fig.

10 3B may be used wherein a single optical tilt-focus error compensator 78 is used instead of two. In this case, the optical tilt-focus error compensator 78 is placed near the midpoint of the overall system, in the light path between AO module 3 and AO module 4, approximately midway between the two modules. Beam 15, resulting from the reflection of beam 9 by AO wavefront corrector 3a, is split by beam splitter 17 into a first part which is directed to AO module 4, and a second part which is directed to WES 3b. WES 3b senses the distortions (e.g., its wavefront errors) of the beam, computes the required correction and addresses the AO wavefront corrector 3a to drive the input distortions to zero or nearly zero, depending on the servo-loop gain of the system. Similarly, beam 16, resulting from the reflection of beam 10 by AO wavefront corrector 4a, is split by beam splitter 18 into a first part which is directed to AO module 3, and a second

15 part which is directed to WES 4b. WES 4b senses the distortions of the beam, computes the

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required correction and addresses the AO wavefront corrector 4a to drive these input distortions to zero or near zero. This is an example of a servo-loop or closed-loop system.

Each AO module is driven or controlled (i.e., configured, in terms of its pixelated phase map) by
5 the respective incident optical beam. AO module 3 is controlled by optical beam 9 originating from station A, while AO module 4 is controlled by optical beam 10 originating from station B.

In order to optimize the efficiency of the system, beam splitters 17 and 18 are preferably
10 designed to transmit most of the incident light (typically in the range of 90% of the incident light, depending on the signal-to-noise ratio (SNR) achieved) to AO module 4 and AO module 3, respectively, while reflecting just enough light to WES 3b and WES 4b, respectively, so that the WESs can function with adequate SNR (i.e., $\text{SNR} > 1$, preferably in the range of 10 to 100 or more).

15 The purpose of the optical tilt-focus error compensators 7 and 8, as shown in Fig 3A, is to remove overall tilt and/or focus errors between the pair of beams, so that they propagate in exact opposition to each other within the system (i.e., they counter-propagate). These compensators 7 and 8 may be omitted if the field-of-view and the dynamic range of the AO modules 3 and 4 provide sufficient correction for lower-order errors (tilt and focus) without compromising the
20 ability to compensate for higher-order wavefront errors on the respective input beams. This

assumes that the AO modules have sufficient dynamic range (i.e, greater than a wave, preferably greater than several waves).

For the purpose of illustration, let us suppose that incident beams 9 and 10, each possesses an arbitrary wavefront error upon incidence onto the respective AO modules 3 and 4. Moreover, let us assume that each beam is encoded with information, in the form of either amplitude or phase modulation. Assume further that the encoded modulation bandwidth exceeds the adaptive optical closed-loop compensation bandwidth, so that the desired modulation is preserved, after beam error compensation. The compensation bandwidth must equal or exceed the distortion effective bandwidth for the system to function. As an example, atmospheric distortions have a time scale on the order of a millisecond, so the AO compensation bandwidth must be greater than 1KHz. On the other hand, the desired communication bandwidth (or link data rate) can be very large (1 to 100 GHz, for example).

The role of the AO module 3 is to minimize, upon reflection/transmission by/through AO module

3, the wavefront errors carried by the input beam 9. For example, AO module 3 will drive the

spatial phase error ϕ_{res} of incident beam 9 to a small residual value dictated by the closed-loop

servo gain G ($\phi_{res} \approx \phi_{in} / (1 + G)$, where ϕ_{in} is the input phase error). The gain G usually ranges

from about 2 to about 100, with higher values of G giving better system performance. The result

of this operation is that a highly aberrated input beam 9, will, after reflection by/transmission

through AO module 3, emerge as a near-plane wave 15. Note that any global phase or intensity

modulation will remain on the planarized (i.e., the scrubbed) beam 15. The planarized beam 15 maintains the globally encoded modulation information. This modulated plane wave 15 will then be reflected/transmitted by/through the other AO module, namely AO module 4. Note that the cleaned-up beam 15 does not affect the spatial phase of AO module 4 since this module is controlled by incident beam 10 originating from station B.

By reciprocity, the plane wave 15 will, upon reflection off/transmission through AO module 4, emerge with the same wavefront as beam 10 had before it reflected off/transmitted through AO 4 . The encoded beam 9 will thus propagate into the precise reverse direction of beam 10 and arrive at station B as a diffraction-limited beam. Diffraction-limited characterizes a beam with highest focusing ability, and is determined by the ratio, λ / D , where λ is the wavelength and D the aperture. Optical distortions increase this ratio by one to several orders of magnitude ($\times 10$ to $\times 1000$, or more) which in turn degrades performance.

The foregoing discussion is also applicable to AO module 4, input beam 10, planarized beam 16 and station A.

In yet another embodiment of the present invention, the two AO wavefront correctors 3a and 4a of Figs. 3A, 3B and 4, are replaced with two regions on a common-focus correction module, as illustrated in Fig. 5. In accordance with this embodiment, the interconnect comprises a common-focus correction module or AO wavefront corrector 34 having a first region 341 and a second

region 342, each region forming a separate AO wavefront corrector. The interconnect further comprises a pair of WESs 34A and 34B, to drive AO wavefront corrector regions 341 and 342 respectively, a pair of optical tilt-focus error compensators 7 and 8, placed upstream of the AO wavefront corrector 34, a pair of beam splitters 38 and 39, and seven reflectors 35, 36, 37, 40, 41, 42 and 43. Tilt-focus error compensator 7 is positioned between station A and AO wavefront corrector 34 such that station A, tilt-focus error compensator 7, and region 341 of the AO Wavefront corrector 34, are substantially aligned. Similarly, tilt-focus error compensator 8 is positioned between station B and AO wavefront corrector 34 such that station B, tilt-focus error compensator 8, and region 342 of the AO Wavefront corrector 34, are substantially aligned.

Beam 91, resulting from the reflection of beam 9 by AO wavefront corrector region 341, is split, by beam splitter 39, into a first part which is directed to AO wavefront corrector region 342 after successive reflection by reflectors 37, 36 and 35, and a second part (beam 92) which is directed to WES 34A after successive reflection by reflectors 42 and 43. WES 34A senses the distortion of the beam, computes the required correction and addresses AO wavefront Corrector region 341 to drive input distortion to zero or near zero. Corrected beam 91 emerges from AO wavefront corrector region 341, substantially distortion free or at least with reduced distortions. Part of beam 91, i.e beam 92, is redirected to WES 34A for further corrections and so on. This illustrates the functioning of a servo-loop or closed-loop system. Similarly, beam 101, resulting from the reflection of beam 10 by AO wavefront corrector region 342, is split, by beam splitter 38, into a first part which is directed to AO wavefront corrector region 341 after successive reflection by reflectors 35, 36 and 37, and a second part (beam 102) which is directed to WES 34B after

successive reflection by reflectors 40 and 41. WES 34B senses the distortion of the beam, computes the required correction and addresses AO wavefront corrector region 342 to drive input distortion to zero or near zero. Corrected beam 101 emerges from AO wavefront Corrector region 342, substantially distortion free or at least with reduced distortion. Part of corrected beam 5 101, i.e., beam 102 is redirected to WES 34B for further corrections and so on.

Each of AO wavefront corrector regions 341 and 342, is driven or controlled (i.e., configured, in terms of its pixelated phase map) by the respective incident optical beam. AO wavefront corrector region 341 is controlled by optical beam 9 originating from station A, while AO wavefront corrector region 342 is controlled by optical beam 10 originating from station B.

In order to optimize the efficiency of the system, beam splitters 38 and 39 are preferably designed to transmit most of the incident light, while reflecting just enough light then sensed by WES 34B and WES 34A, respectively, so that the WESs can function with a adequate signal-to-noise ratio.

The purpose of the optical tilt-focus error compensators 7 and 8, is to remove overall tilt and/or focus errors between the pair of compensated beams, so that they propagate in exact opposition to each other within the system (i.e., they counter-propagate). These compensators 7 and 8 may 20 be omitted if the field-of-view and the dynamic range of the AO wavefront corrector 34 provides sufficient correction for these lower-order errors (tilt and focus) without compromising the

ability to compensate for the higher-order wavefront errors on the respective input beams. This assumes that the AO wavefront corrector 34 has sufficient dynamic range.

For the purpose of illustration, let us suppose that incident beams 9 and 10, each possesses an arbitrary wavefront error upon incidence onto the respective AO wavefront corrector regions 341 and 342. Moreover, let us assume that each beam is encoded with useful global information, in the form of either amplitude or phase modulation. We further assume that the encoded modulation bandwidth exceeds the adaptive optical closed-loop compensation bandwidth, so that the desired modulation is preserved, after beam clean-up. The compensation bandwidth must equal or exceed the distortion effective bandwidth for the system to function. As an example, atmospheric distortions have a time scale on the order of a millisecond, so the AO compensation bandwidth must be greater than 1KHz. On the other hand, the desired communication bandwidth (or link data rate) can be very large (1 to 100 GHz, for example).

- 15 The role of the AO wavefront corrector region 341 (342, respectively) and WES 34A (34B, respectively) is to minimize, upon reflection by AO wavefront corrector region 341 (342, respectively), the wavefront errors carried by the input beam 9 (10, respectively). That is, AO wavefront corrector region 341 (342, respectively) will drive the spatial phase error ϕ_{res} of incident beam 9 (10, respectively) to a small residual value dictated by the closed-loop servo
- 20 gain G ($\phi_{res} \approx \phi_{in} / (1 + G)$, where ϕ_{in} is the input phase error). The gain G usually ranges from about 2 to about 100, higher values giving better system performance. The result of this

operation is that a highly aberrated input beam 9 (10, respectively), will, after reflection by AO wavefront corrector region 341 (342, respectively), emerge as a near-plane wave 91 (101, respectively). Note that any global phase or intensity modulation will remain on the planarized (i.e., the scrubbed) beam 91 (101, respectively). The planarized beam 91 (101, respectively) maintains the globally encoded modulation information. This modulated plane wave 91 (101, respectively) will then be reflected by reflectors 37, 36, and 35 (35, 36, and 37, respectively) and finally by the other AO wavefront corrector region, namely AO wavefront corrector region 342 (341, respectively) which directs corrected modulated plane wave 91 (101, respectively) to its final destination, i.e., station B (station A, respectively). Note that the cleaned-up beam 91 (101, respectively) does not affect the spatial phase of AO wavefront corrector region 342 (341, respectively) since this region is controlled by incident beam 10 (9, respectively) originating from station B (A, respectively).

By reciprocity, plane wave 91 (101, respectively) will, upon reflection by AO wavefront corrector region 342 (341, respectively), emerge with the same wavefront as beam 10 (9, respectively) had before it reflected off AO wavefront corrector region 342 (341, respectively).

The encoded beam 9 (10, respectively) will thus propagate into the precise reverse direction of beam 10 (9, respectively) and arrive at station B (A, respectively) as a diffraction-limited beam. Diffraction-limited characterizes a beam with highest focusing ability, and is determined by the ratio, λ / D , where λ is the wavelength and D the aperture. Optical distortions increase this ratio

by one to several orders of magnitude ($\times 10$ to $\times 1000$, or more) which in turn degrades performance.

The different types of AO modules suitable for the embodiments previously described, include
5 reflective devices such as Liquid Crystal Light Valves (LCLVs) or LC pixelated phase shifters, which can be optically or electrically driven on a pixel-by-pixel basis, liquid crystal Spatial Light Modulators (SLMs), deformable MEMS devices, or optical MEMS-based SLMs. Suitable AO modules may also include transmission devices such as liquid crystal cells with transparent electrodes or any combination of the these devices. Conventional wavefront error sensors may also be used which drive deformable mirrors (e.g., PZT-activated, etc.). Regardless of which devices are used, an incident beam will emerge from each AO module with its wavefronts planarized.

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Possible wavefront error sensors include conventional shearing interferometric sensor, a *Shack-Hartmann* (local tilt) sensor, or a holographic intensity-to-phase sensor.

Possible global tilt-focus error compensator (used for bore-sighting) include a pair of tilt mirrors (conventional, optical MEMS, etc.), a pair of real-time liquid crystal gratings, etc., which are driven by a standard closed-loop quad detector-based servo loop.

The various elements comprised in the interconnection system are preferably packaged in a compact structure. The distances between the two stations and the interconnection system may be large, however.

- 5 The system of the present invention acts as an optical interconnect, essentially coupling the two beams that emanate from their respective transceivers (stations), while maintaining their encoded information. Each beam leaves the interconnection system in the form of a phase-conjugate replica of the other beam; yet, the temporal encoding on each beam is preserved. Since the pair of AO modules 3 and 4, or regions 341 and 342, are locally controlled by input beams 9 and 10 respectively, the two beams do not need to be coherent or even have the same nominal wavelength (the allowed wavelength difference is governed by the dispersion and diffraction of the system, and the propagation path characteristics for a given range). Thus, the system can function in the presence of differential Doppler shifted beams, emanating from platforms moving at different speeds, as well as with general beam wander and propagation errors.

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- The system can also function in guided-wave architectures, providing dynamic coupling of information from one fiber (or waveguide) channel to another, or to a plurality of channels. All that is required is that a given channel provide a reference or beacon beam so that the AO module can planarize the beam and, at the same time, provide for a phase-conjugate return of the temporally encoded beam back to the reference beam point of origin.

Having described the invention in connection with certain embodiments thereof, modifications will certainly suggest themselves to those skilled in the art. As such, the invention is not to be limited to the disclosed embodiments except as required by the appended claims.